

The Neutral ISM in Starburst Galaxies
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HI on large and small scales in *starburst* radio galaxies

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Abstract. The study of the optical continuum of radio galaxies shows that about 30% have a young stellar population component. Among them are the most far-IR bright radio galaxies. A further indication of the relatively gas rich environment of these galaxies (possibly related to the recent merger from which they originate) is the high fraction being detected in HI.

Here we present recent results obtained from the study of neutral hydrogen (detected either in emission or absorption) in a group of starburst radio galaxies. In some objects, large-scale (tens of kpc) structures involving HI masses exceeding $10^9 M_\odot$ are observed. In these cases, the HI can be used to study the origin and evolution of these systems and the timescales involved. In this respect, the parameters obtained from the study of the stellar populations and from the HI can be complementary. In other objects, very broad ($\gtrsim 1000$ km/s), mostly blueshifted HI is detected in absorption. This result shows that, despite the extremely energetic phenomena occurring near an AGN - including the powerful radio jet - some of the outflowing gas remains, or becomes again, neutral. This can give new and important insights in the physical conditions of the gaseous medium around an AGN. The possible origin of the extreme kinematics is discussed.

1. Preamble: *Starburst* radio galaxies

What we will call *starburst* radio galaxies in this brief review are radio sources hosted by galaxies that spectroscopically show a young stellar population component in addition to the old component typical of elliptical galaxies. These

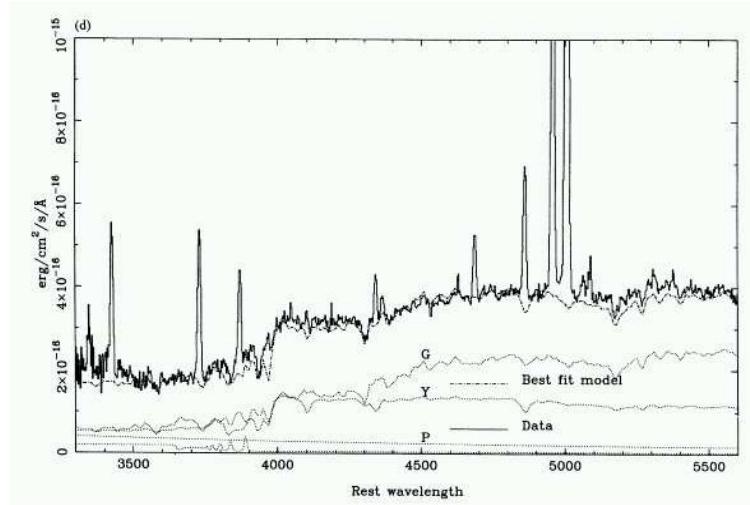


Figure 1. The (rest-frame) intensity spectrum of 3C 321 (from Tadhunter et al. 1996) with superimposed the model of the continuum - the best-fitting combination of a 15-Gyr (G), power-law (P), nebular continuum (N) and a 1-Gyr starburst component (Y). See Tadhunter et al. (1996) for details.

objects are now known to represent a significant fraction of samples of radio galaxies (see below). Their relevance, and the motivation for our study, has to do with the more general and important question of what is the origin and evolution of radio galaxies.

From imaging studies of powerful radio galaxies (Heckman et al. 1986), there is clear morphological evidence that their host galaxies have undergone interactions and/or mergers. Because of this, it has been suggested that these phenomena are in fact responsible for the onset of the radio sources. In this scenario it is not too surprising that starformation is also triggered by the same merging event. The presence of a young stellar population has an other important implication: it could represent the origin of the UV excess found to be typical of radio galaxies compared to normal ellipticals (Lilly & Longair 1984) - as alternative to the anisotropic scattering model of the quasar radiation (see e.g. Tadhunter, Fosbury & di Serego Alighieri 1988).

Until not so long ago, only a handful of radio galaxies were known, from optical spectroscopy, to have a young stellar population in their nuclear regions (see e.g. 3C 321 Tadhunter et al. 1996, Hydra A Melnick et al. 1997). Given the importance of understanding how common this is, we have recently undergone systematic studies of the stellar population in radio galaxies (Tadhunter et al. 2002, Wills et al. 2002). Because in radio galaxies key absorption features (sensitive to the presence of young stellar population) are in most cases filled in by strong emission lines, the study of the stellar population is better done using the modelling of the entire continuum SED (see Tadhunter et al. 1996 for more details).

Figure 2a,b,c in separate .gif files

Figure 2. Examples of HI distribution around “normal” early-type galaxies obtained from the ATCA follow up of HIPASS detections (see text for details). Contour levels: $2, 4, 8, 16 \times 10^{19} \text{ cm}^{-2}$.

The results show that a young stellar population component is present in at least 30% of radio galaxies. The typical ages of the young stars is between 0.5 and 2 Gyr. Interestingly, the galaxies showing this component are also the most luminous in the far-IR, indicating a link between the optical starburst and the far-IR emission. This relatively large fraction is also consistent with the results obtained - using HST - from the UV morphology of powerful 3CR radio galaxies, where clear regions of starformation are often observed (Allen et al. 2003). These results support the idea of a merger origin for radio galaxies and suggest that, at least some of them, had an (ultra-) luminous far-IR galaxy as progenitor (Tadhunter et al. 2002, Wills et al. 2002). The results also indicate that the activity starts late after the merger event. The existence of galaxies where this young stellar component is not observed indicates that, if they are merger related, they are observed at a later stage and/or they originate from other type of mergers. In summary, the study of starburst radio galaxies provides important clues on the origin and evolution of radio galaxies.

As we will see below, the study of the neutral hydrogen in *starburst* radio galaxies gives complementary information to that provided by the optical stellar population. Neutral hydrogen has the main advantage that it traces the large-scale distribution of the gas as well as the ISM conditions in the nuclear regions near the AGN. Preliminary results show that in *starburst* radio galaxies the presence of HI - mainly, but not only, detected in absorption against the central regions - is more common compared to other radio galaxies (Morganti et al. 2001) and this has motivated the studies that will be reviewed here.

2. Large-scale structures of neutral hydrogen

HI detected at large radii (tens of kpc) is a long-lived signature of a merger/interaction and therefore provides a key diagnostic of how a galaxy formed. Large-scale HI structures have been found in a growing number of nearby “normal” (i.e. radio quiet) early-type galaxies (see e.g. Oosterloo et al. 2002) and in many cases the likely origin is a major-merger event. What is (if any) the relation between these gas-rich systems and radio galaxies? If radio galaxies - and in particular starburst radio galaxies - indeed originate from (major) mergers, and the radio

activity is just a short phase in the evolution of the host galaxy, fossil large-scale HI structures similar to those detected in “normal” early-type might be expected.

A systematic study of the occurrence of large HI structures in radio galaxies, and *starburst* radio galaxies (to be compared with the results for normal galaxies of similar type) is now in progress (Emonts et al. in prep). The results may also shed some light on the importance of the initial conditions and/or environment for the evolution of the galaxy. For example, it has been claimed that the capability of a merger to bring gas into the nuclear (pc) regions - and therefore produce an AGN - depends on the structure (e.g. the presence of a bulge) of the progenitor (Mihos & Hernquist 1994).

Although we do not have yet complete statistics, here we present the results for two interesting cases of *starburst* radio galaxies that we have recently studied. First, however, lets summarise briefly what has been found so far for ”normal” early-type galaxies.

2.1. Large-scale HI in “normal” early-type galaxies: a brief summary

A recent systematic study of HI in all southern RC3 early-type galaxies detected by the HIPASS survey (see Oosterloo et al. 2003 for details), has brought to some surprising and interesting results. Among the detected galaxies (between 6 and 14 % depending on the optical classification) a wide range of HI morphologies is found, but a surprisingly large fraction shows huge structures (many tens of kpc and up to 200 kpc) in the form of regularly rotating disks containing a large amount of HI ($> 10^9 M_{\odot}$). Some examples are shown in Fig. 2. Similar structures previously observed in other early-type galaxies (Morganti et al. 1997, Oosterloo et al. 2002) were explained as originating from a major-merger event involving at least one gas-rich disk galaxy. Given that the HI appears often quite settled, the gas must have already completed at least few orbits ($\sim 10^9$ yr) and the merger must be relatively old. Actually, for the huge HI structures shown in Fig. 2, a few orbits in the outer regions of the disk already imply extremely long timescales (several times 10^9 yr), that may not be always easy to reconcile with the merger hypothesis. From the observed parameters a “first-order” evolution sequence can be build to connect these objects (e.g. NGC 5266 Morganti et al. 1997) with well-known major mergers that are observed in an initial phase (e.g. NGC 7252 or the Antennae; Hibbard & van Gorkom 1996, Hibbard et al. 2001 respectively).

2.2. Starburst radio galaxies and large scale HI

There are only an handful of very nearby radio galaxies where large-scale HI structures have been detected so far: for example PKS B1718-649 (Véron-Cetty et al. 1995), Centaurus A (Schiminovich et al. 1994 and refs therein) and, at lower radio power, NGC 4278 (Raimond et al. 1981) and NGC 1052 (van Gorkom et al. 1986). In addition to these, Coma A was the first case where in a powerful radio galaxy a large HI structure was detected in absorption (Morganti et al. 2002a). It is interesting that in our study of HI in starburst radio galaxies we have found already two more interesting cases of extended HI - one detected in emission and one in absorption.

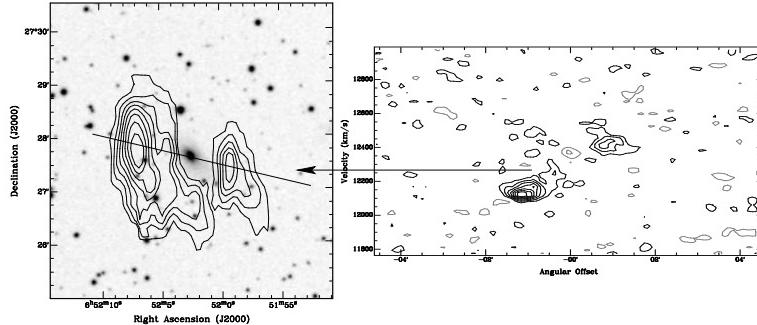


Figure 3. *Left:* HI total intensity contours (from the WSRT) of the radio galaxy B2 0648+27 superimposed on to an optical image. *Right:* Position-velocity plot along the major axis.

In the nearby ($z = 0.041$) starburst radio galaxy B2 0648+27, HI is detected - using the WSRT - both in emission and in absorption (Morganti et al. 2003a). In emission, we detect a large amount of HI ($M_{\text{HI}} = 1.1 \cdot 10^{10} M_{\odot}$) distributed in a very extended disk, or ring-like structure, of about 160 kpc in size, as shown in Fig. 3. We also detect HI absorption against the central radio continuum component. The characteristics of the detected HI, and the similarities with some of the “normal” elliptical mentioned above, are explained as the result of a major merger. The structure of the HI and the asymmetric density distribution, however, suggest that the HI is not yet in a completely settled configuration. We can derive a rough indication of the age of the merger of at least few times 10^8 yr and it may represent a merger in an intermediate stage (Morganti et al. 2003a): between major mergers in their early phase - like the Antennae - and galaxies with more settled HI structures like, e.g., NGC 5266 (Morganti et al. 1997). This is illustrated in Fig. 4. Interestingly, the radio source shows all the characteristics of being much younger (compact and steep spectrum, see O’Dea 1998 for a review), $<< 10^7$ yrs old. This supports the idea that the radio source appears late after the merger but also that, under favourable conditions, the HI gas can stay around for very long time. Indeed, it is interesting to note that in B2 0648+27, as in the other systems mentioned above, the column density of the HI detected in emission is relatively low (only $\sim 0.8 M_{\odot} \text{pc}^{-2}$) as in the other gas-rich elliptical galaxies (see e.g. Oosterloo et al. 2002). Therefore, no significant star formation is, at present, occurring in the regions coincident with the HI. The galaxy can, therefore, remain gas rich for a very long period.

A different case appears to be 3C 433. Extended HI in absorption has been observed against the southern radio lobe of this starburst radio galaxy. The preliminary analysis of the data (Fig. 5) shows that $\sim 5 \times 10^8 M_{\odot}$ of (extended) HI is detected in absorption at about 60 kpc from the radio core. The gas shows a velocity gradient, but at the moment it is not clear whether the detected HI is part of an extended gas disk/tail or whether it corresponds to a region of interaction between the ISM and the radio lobe. Given the smaller amount of HI detected in this object, the origin of this galaxy might be different from the major-merger suggested for B2 0648+27. It is interesting to note that 3C 433

Figure 4 in a separate .gif file

Figure 4. Possible evolutionary sequence (from Morganti et al. 2003a) linking gas-rich mergers with radio galaxies and gas-rich ellipticals (described in text). The images of the Antennas and NGC 7252 have been taken from Hibbard & van Gorkom (2001), B2 0648+27 from this paper, NGC 5266 from the data presented in Morganti et al. (1997).

Figure 5 in a separate .gif file

Figure 5. The total intensity image (grey scale) of the H I absorption in 3C 433, superimposed on to the radio continuum (contours). On the right is shown the position-velocity plot taken along the line marked on the zoom-in image in the middle.

is part of a dumbbell system (Parma et al. 1991) and has a relatively young stellar population (0.1 Gyr, Wills et al. 2002).

At the moment information on large-scale H I is limited to only two objects, but our aim is to extend this study to many more radio galaxies and to be able to identify possible trends.

3. HI in the nuclear regions of starburst radio galaxies

H I at small radii (\sim kpc, i.e. nuclear scales) has been detected in absorption against the strong radio continuum in many radio galaxies in a number of studies (e.g. Vermeulen et al. 2003, Morganti et al. 2001 and refs therein for previous studies). This neutral hydrogen has been often associated with gas distributed in a nuclear disk or torus. However, recent observations indicate that such an

interpretation cannot always be applied and the situation can be much more complex (Morganti 2002b and refs therein).

In this respect, our initial results on HI in the central region of *starburst* radio galaxies are interesting. In particular, the combined study of the ionized and the neutral gas has revealed to be crucial for the understanding of the physical conditions of the ISM in the central regions of radio galaxies. A clear example is the southern, *starburst* radio galaxy PKS 1549-79. In this object, two redshift systems of ionized gas were found (Tadhunter et al. 2001). The HI absorption has the same redshift as the low ionisation gas, while the high ionisation gas appears blueshifted respect to it. The HI absorption is associated with a cocoon of material surrounding the tiny (~ 200 pc in size) radio source. The material is believed to be left over from the event that triggered the radio source. The highly ionized material is instead associated with a nuclear outflows.

3.1. Fast HI outflows

Even more intriguing is the discovery, in at least two *starburst* radio galaxies, that the presence of fast outflows is associated not only with ionized gas but also with neutral gas. This finding gives new and important insights on the physical conditions of the gaseous medium around an AGN.

A good example is the young, *starburst* radio galaxy, 4C 12.50. The fast HI outflow was detected using the broad band (20 MHz) system now available at the Westerbork Synthesis Radio Telescope (WSRT). Due to the much stronger radio continuum of this radio galaxy, detection of gas at very low optical depth is possible. 4C 12.50 is a particularly interesting object as it is a prime candidate for the link between ultraluminous infrared galaxies (ULIGs, Sanders & Mirabel 1996) and radio galaxies (Evans et al. 1999). The radio source is confined to a region < 0.1 arcsec (~ 240 pc) and has all the characteristics of young radio sources ($<< 10^7$ yr). The ISM of this radio galaxy is extremely rich: it is the most far-IR bright radio galaxy and has a high molecular gas mass (Evans et al. 1999). A “stratified” fast outflow of the highly ionized gas, that is quite similar to that detected in PKS 1549-79, has been detected by Holt et al. (2003). In Fig. 6a is presented the HI absorption detected with the WSRT. The absorption appears clearly complex and *extremely broad*. The full range of velocities covered by the HI absorption is $\sim 2000 \text{ km s}^{-1}$, the broadest detected so far in HI. The peak optical depth of the broad component is only $\tau \sim 0.002$ and the column density of the full system of shallow HI absorption (assuming a covering factor is 1) is $\sim 1.7 \times 10^{20} T_{\text{spin}}/100K \text{ cm}^{-2}$.

A similar situation (fast outflow of both ionized and neutral gas) is also seen in the *starburst* radio galaxy 3C 293 that, although it is not classified as young, is nevertheless believed to have recently experienced a restarting radio activity (see also Emonts et al. these Proceedings). Again using the new broad band (20 MHz) system available at the WSRT, broad, mainly blueshifted, HI absorption has been detected (see Morganti et al. 2003b and Emonts et al. these proceedings for details). The absorption profile is shown in Fig. 6b. The broad HI absorption has a full-width at zero intensity (FWZI) of $\sim 1400 \text{ km s}^{-1}$. It is very shallow, with a typical optical depth of only ~ 0.0015 , and, assuming a covering factor is 1, a column density of the HI is $\sim 2 \times 10^{20} T_{\text{spin}}/100 K \text{ cm}^{-2}$. As in the case of 4C 12.50, this gives a lower limit to the true column

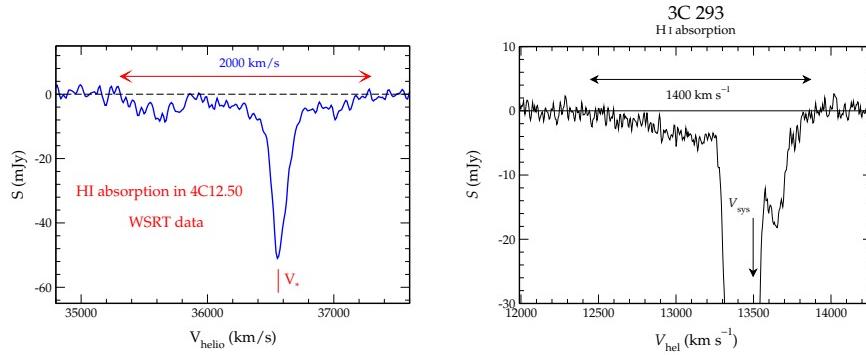


Figure 6. The HI absorption profile detected in 4C 12.50 (left) and 3C 293 (right) from the WSRT observations. The spectra are plotted in flux (mJy) against optical heliocentric velocity in km s^{-1} .

density as the T_{spin} associated with such a fast outflow can be as large as a few 1000 K (instead of 100 K which is more typical of the cold, quiescent HI in galaxy disks).

These two galaxies are the first examples of radio galaxies where a fast HI outflow is observed, but more candidates exist among starburst radio galaxies. This result shows that, despite the extremely energetic phenomena occurring near an AGN - including the powerful radio jet - some of the outflowing gas remains, or becomes again, neutral.

3.2. What produces the HI outflows?

Outflows of ionized gas appear to be a relatively common characteristic in AGN and starburst galaxies (as also illustrated by a number of talks in this conference). Fast gas outflows are now detected (in optical, UV and X-ray observations) in a wide range of AGNs, from Seyfert galaxies to quasars (see e.g. Crenshaw et al. 2001; Turnshek 1986; Krongold et al. 2003 and refs therein). These outflows can be produced by different and highly energetic phenomena, such as interaction of the radio plasma with the ISM as well as nuclear and/or starburst winds. It is interesting to see that HI outflows have been also detected in HI, but so far are only found in starburst radio galaxies. This might be due to the presence of a particularly rich ISM that characterises radio galaxies in this stage of their evolution, with the rich ISM possibly resulting from a recent merger.

The central question is how *neutral* gas can be associated with such fast outflows. A possible model is that the radio plasma jet hits a (molecular) cloud in the ISM. As a consequence of this interaction, the kinematics of the gas is disturbed by the shock and perhaps part of the gas is also ionized by it. Once the shock has passed, part of the gas may have the chance to recombine and become neutral, while it is moving at high velocities (see Fig. 7). In the model proposed by Mellema et al. (2002), as the shock runs over a cloud, a compression phase starts because the cloud gets embedded in an overpressured cocoon. The shock waves start travelling *into* the cloud and the cloud fragments with the fragments moving at high velocities. The cooling times for the dense fragments are very

short (few times 10^2 years) compared to the lifetime of the radio source and that the excess of energy is quickly radiated away. This results in the *formation of dense, cool and fragmented structures at high velocities*.

As indirect support to this hypothesis, it is worth mentioning that in the only other case of broad blueshifted HI absorption (of 700 km s^{-1} FWZI) studied in detail so far, the Seyfert galaxy IC 5063 (Oosterloo et al. 2000), the HI absorption is coincident with the brighter radio lobe where also the most kinematically disturbed ionized gas is observed. This supports the idea of jet/cloud interaction as most likely mechanism in this Seyfert galaxy. Another possible example is the Seyfert galaxy Mrk 1 (Omar et al. 2002). However, it is not yet clear whether with the mechanism proposed above it is really possible to accelerate the clouds to the high velocities observed. Therefore, other possibilities should be considered:

i) *Starburst*: Given the presence of a young stellar population in these galaxies, a starburst wind capable to accelerate the gas should be considered to explain the HI outflow. This mechanism is indeed known to produce fast outflow at least of ionized gas (see e.g. Heckman, Armus & Miley 1990, and Veilleux these proceedings). However, in the case of *starburst* radio galaxies the age of the young stellar population component has been estimated between 0.4 and 2.5 Gyr. Thus, the neutral outflow would have to be a “fossil” starburst-driven wind from the strong starburst that may have occurred of the order of 1 Gyr ago. Given this condition, it is not clear whether the starburst-driven outflow would survive to the present day and, more important, whether it would be still seen against the central regions.

ii) *Radiation pressure from the AGN*: Dopita et al. (2002) have explored the possibility that the narrow-line regions in active galaxies are actually dusty and that the radiation pressure acting over the dust could produce the extreme kinematics observed in the ionized gas. In their model they consider a dusty (radiation pressure-dominated) region surrounding a (photoevaporating) molecular cloud. In this scenario, the dust is estimated to survive as the average gas temperature does not exceed 10^4 – unlike the case of fast shocks – and it will not destroy the grains in the short time during the passage through the high-emissivity region. While for 4C 12.50 the strong AGN suggest that this mechanism could be considered as an option, in 3C 293, the very low ionisation and faint emission lines suggest that the UV radiation from the AGN is not that strong and therefore unlikely to provide the necessary pressure to produce the outflow.

iii) A further possibility is that the HI outflow is associated to the adiabatically expanded broad emission line clouds (BELCs) as suggested by Elvis et al. (2002). Following their work, if the broad emission line region is outflowing, then the BELCs will expand and cool adiabatically, and will reach 1000 K at \sim few pc. They will then form dust and also neutral hydrogen but in this case the HI outflow has to be located very close to the nucleus.

In summary, in order to identify which mechanism is the more likely to accelerate the gas, the exact location of the broad HI absorption is needed and VLBI follow-up observations are now in progress.

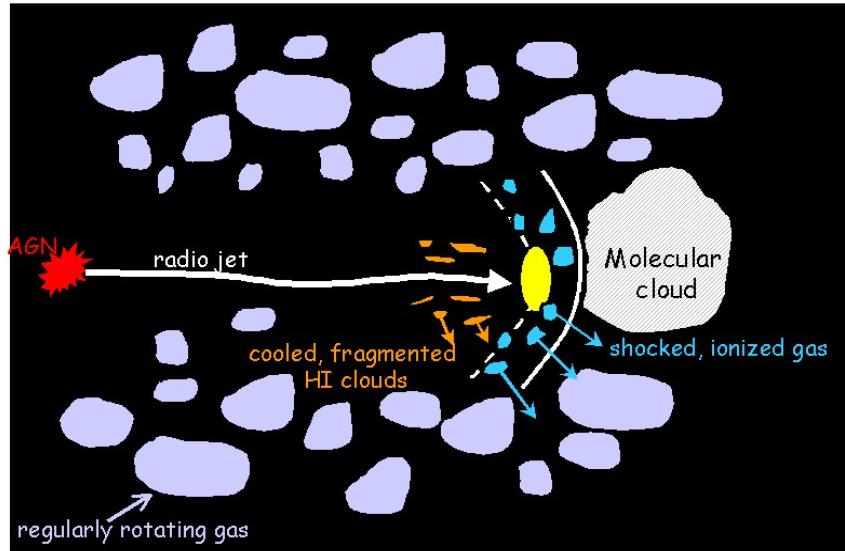


Figure 7. A schematic diagram of the model proposed for the *starburst* radio galaxies discussed in the test where outflows of neutral and ionized gas have been detected.

4. Final remarks

In this review we have shown that the group of *starburst* radio galaxies is a particularly interesting one in order to understand the origin and evolution of radio galaxies. The study of neutral hydrogen in this group of objects is also giving us important clues about these open questions. HI appears to be relatively common in *starburst* radio galaxies (at least compared to other radio galaxies). We interpret this as an indication that large amount of gas is still around from the merger that triggers the radio source.

We have presented two cases in which extended HI has been detected. The case of B2 0648+27 represents one of the largest HI disks known (~ 160 kpc) around a radio galaxy with more than $10^{10} M_{\odot}$ of HI. It shows that at least some radio galaxies are likely the results of major mergers and that the AGN activity appears late after the merger.

Even more surprising is the finding of fast HI outflows in at least two *starburst* radio galaxies. This result shows that, despite the extremely energetic phenomena occurring near an AGN - including the powerful radio jet - some of the outflowing gas remains, or becomes again, neutral. This can give new and important insights on the physical conditions of the gaseous medium around an AGN.

Following these results, a tantalising connection can be made with the high- z radio galaxies. As in the *starburst* radio galaxies presented here, there is clear evidence for the presence of large amounts of cold gas and, in general, for the presence of a rich gaseous environment in radio galaxies at high redshift (see e.g. van Breugel 2000 for a review). Particularly relevant is the finding

(Villar-Martíñ et al. 2002) of a low surface brightness Ly α halo with quiescent kinematics in the case of the high- z radio galaxy USS 0828+193. One possible way suggested to explain this structure is that the low surface brightness Ly α halo is the progenitor of the HI discs as found in the case of B2 0648+27 and others discussed above. If this is the case, the wealth of details that we can learn at low- z may be crucial for understanding the structures at high- z . Moreover, strong interactions between the radio plasma and the medium are expected to be very important in high- z objects. Outflow phenomena have been detected in many high-redshift radio galaxies. In many cases, asymmetric Ly α profiles suggest the presence of blueshifted absorbing gas (likely neutral hydrogen; see van Ojik et al. 1997, de Breuck et al. 1999). Additionally, complex gas kinematics is also observed in a large fraction of high- z radio galaxies (van Ojik et al. 1997). Thus, similar processes as observed in 4C 12.50 and 3C 293 are likely to be even more common in these high- z systems. Understanding the physics of fast gas outflows and the conditions for which part of the outflowing gas is neutral, can be also relevant for understanding high- z objects.

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